Measurement of the Beam-Normal Single Spin Asymmetry in Deep Inelastic Scattering using the SoLID Spectrometer

On behalf of

William Henry[1], Michael Nycz[2], Ye Tian[3], Weizhi Xiong[4], Xiaochao Zheng[2]

[1]Jefferson Lab

[2]University of Virginia

[3]Syracuse University

[4]ShandongUniversity

UNIVERSITY of VIRGINIA

PAC 50

07/12/2022

A Hall A and SoLID proposal

Beam-Normal Single Spin Asymmetries and TPE

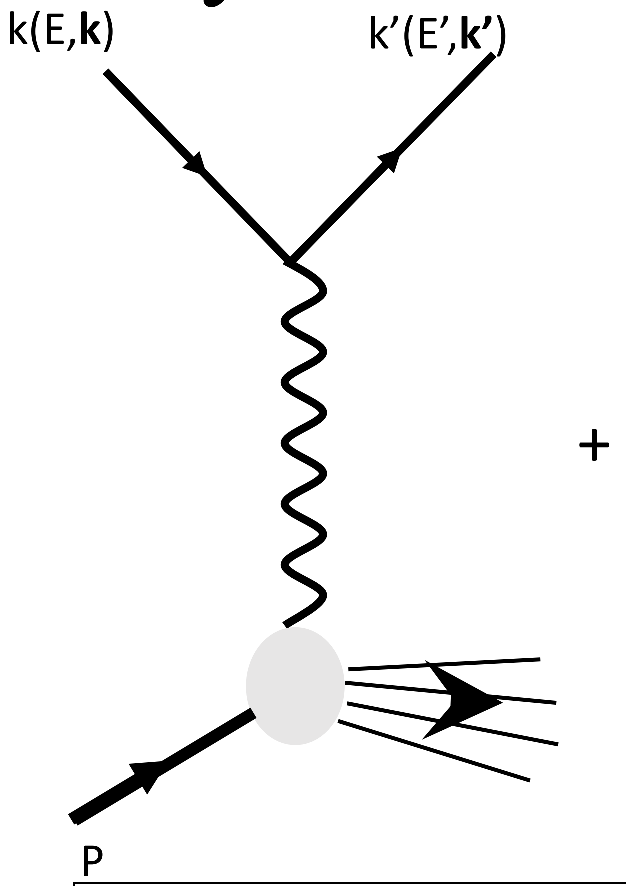
- Beam-normal SSA is an observable generated from the interaction between:
  1. e^- polarized ⊥ to scattering plane
  2. Unpolarized target

$$\frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}$$

Beam-Normal Single Spin Asymmetries and TPE

- Beam-normal SSA is an observable generated from the interaction between:
  1. e$^-$ polarized ⊥ to scattering plane
  2. Unpolarized target
- Beam- (and target) normal SSA are zero at Born level
  - N. Christ and T.D. Lee., Phys. Rev. 143 (1965)

$$\frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}} = 0$$



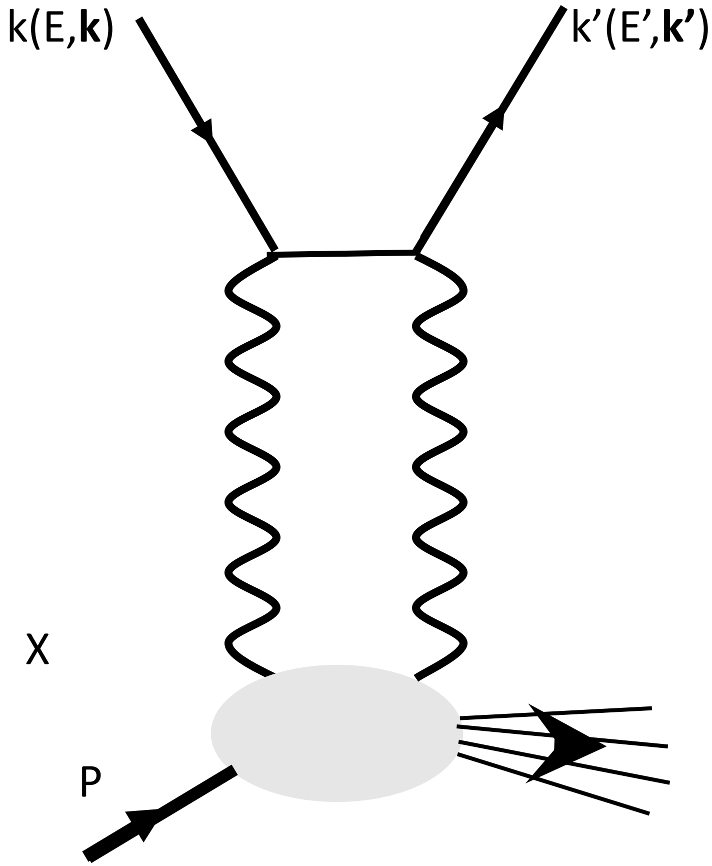
$$A_n \propto \epsilon_{\gamma\delta\lambda\mu} S^{\gamma} P^{\delta} k^{\lambda} k'^{\mu}$$

S= spin of the e$^-$
P= four-momentum of target
$k(k')$ = four-momentum of incident (scattered) e$^-$

Beam-Normal Single Spin Asymmetries and TPE

- Beam-normal SSA is an observable generated from the interaction between:
  1. e⁻ polarized ⊥ to scattering plane
  2. Unpolarized target
- Beam- (and target) normal SSA are zero at Born level
  - N. Christ and T.D. Lee., Phys. Rev. 143 (1965
- Beyond born level, beam- (and target) SSA can be non-zero

$$\frac{\sigma^{\uparrow}-\sigma^{\downarrow}}{\sigma^{\uparrow}+\sigma^{\downarrow}} \neq 0$$

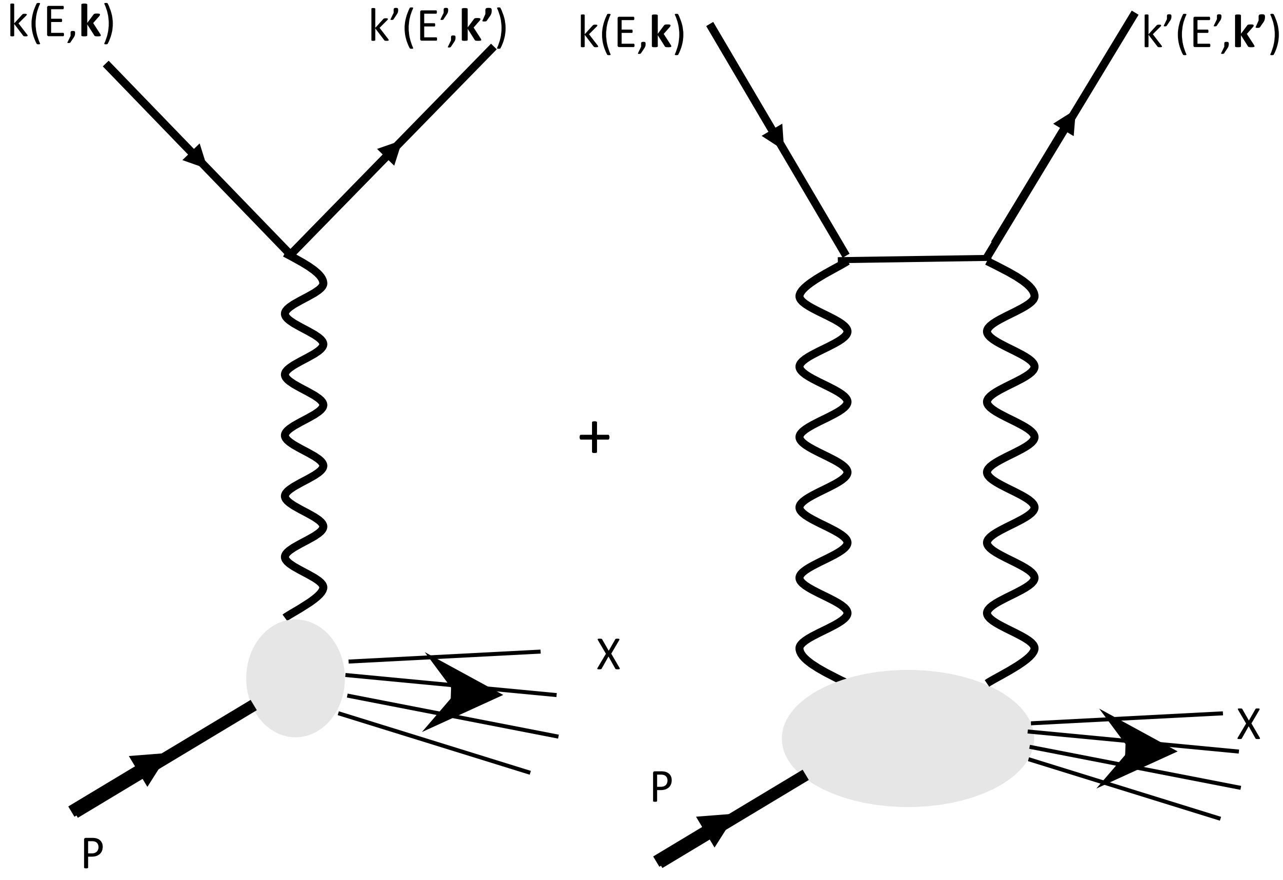


$$A_n \propto \epsilon_{\gamma\delta\lambda\mu} S^{\gamma} P^{\delta} k^{\lambda} k'^{\mu}$$

S= spin of the e⁻
P= four-momentum of target
$k(k')$ = four-momentum of incident (scattered) e⁻

Beam-Normal Single Spin Asymmetries and TPE

- Beam-normal SSA is an observable generated from the interaction between:
  1. e^- polarized ⊥ to scattering plane
  2. Unpolarized target
- Beam- (and target) normal SSA are zero at Born level
  - N. Christ and T.D. Lee., Phys. Rev. 143 (1965
- Beyond born level, beam- (and target) SSA can be non-zero
- Are due to the interference of single and two photon exchange processes
  - Normal single-spin asymmetries provide access to the **imaginary** part of the TPE



$$A_n \propto \boldsymbol{Im}\, T_{1\gamma} T_{2\gamma}^*$$

Beam-Normal Single Spin Asymmetries

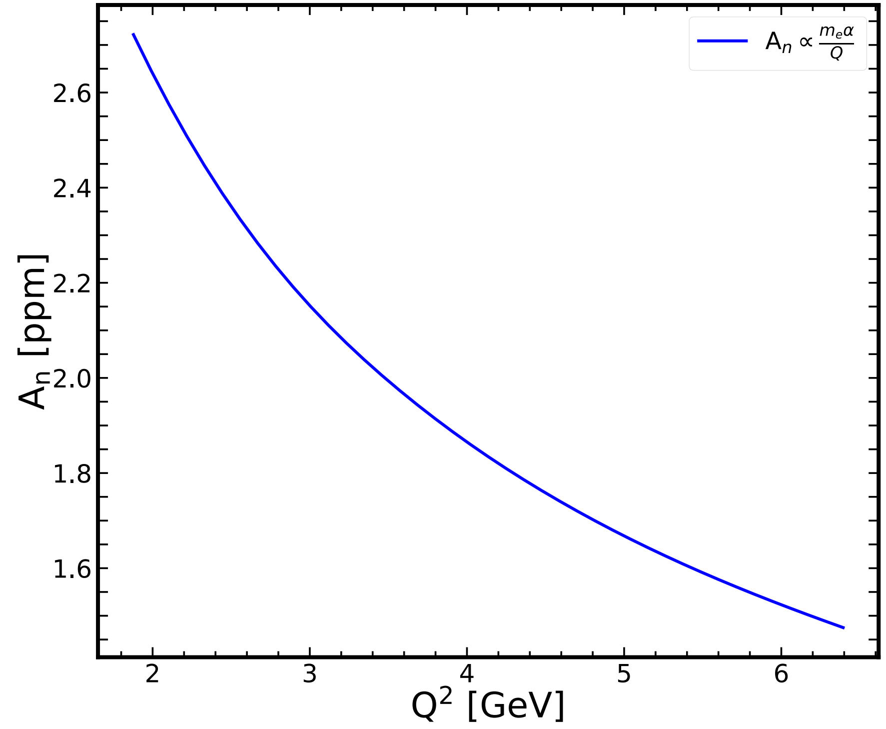
1. Non-zero BNSSA in DIS?
2. Dominant mechanism?
   - Two photon exchange occurs between lepton and the same quark?
   - Two photon exchange occurs between lepton and different quarks?
   - A full understanding of normal single spin asymmetries could have implications on TMD studies
3. First precision measurement in DIS (past measurements in elastic only)

Theoretical Predictions

- $A_n = \frac{\alpha_{\mathrm{EM}} m}{2Q}$

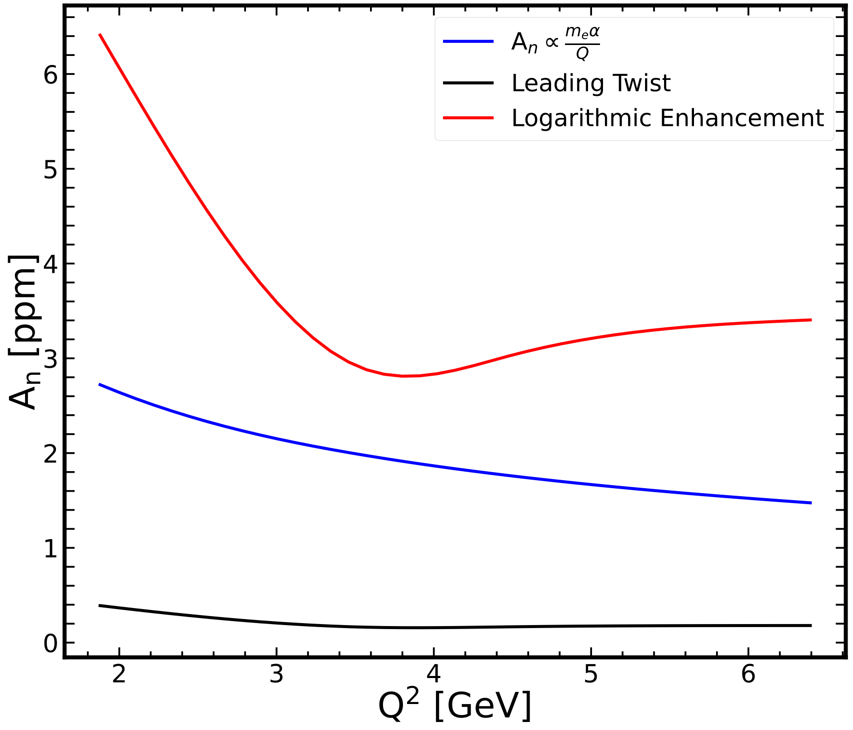
Theoretical Predictions

- $\mathrm{A}_n = \frac{\alpha_{\mathrm{EM}} m}{2Q}$



Theoretical Predictions

- Beam-normal prediction: Exchange of two photons occurs between lepton and the same quark
  - $A_n = \frac{\alpha_{\text{EM}} m_l |\vec{S}_T| \sin(\varphi_s)}{2Q} \frac{y^2\sqrt{1-y}}{1-y+\frac{1}{2}y^2} \frac{\sum_q e_q^3 q(x)}{\sum_q e_q^2 q(x)}$
  - A. Metz et al., Phys. Lett. B 643 (2006)
  - Prediction for A_n: 10^{-6}-10^{-7}



Theoretical Predictions

- Beam-normal prediction: Exchange of two photons occurs between lepton and the same quark
  - $A_n = \frac{\alpha_{\text{EM}} m_l |\vec{S}_T| \sin(\varphi_s)}{2Q} \frac{y^2\sqrt{1-y}}{1-y+\frac{1}{2}y^2} \frac{\sum_q e_q^3 q(x)}{\sum_q e_q^2 q(x)}$
  - A. Metz et al., Phys. Lett. B 643 (2006)
  - Prediction for A_n: 10^{-6}-10^{-7}
- Target-Normal Predictions (Neutron):
  1. Exchange of two photons occurs between lepton and the same quark
     - A. Afanasev et al., Phys. Rev. D77 (2008) : TNSSA ~ 10^{-4}
  2. Exchange of two photons occurs between lepton and different quarks
     - A. Metz et al. Phys. Rev. D86 (2012):TNSSA ~ 10^{-2}

JLab 6 GeV target- normal SSA (Neutron)	Hermes target-normal SSA (Proton)
$(-1.09 \pm 0.38) \times 10^{-2}$ (Non-zero: 2.89σ)	$(0.6 - 0.9) \pm (1.50 - 3.97) \times 10^{-3}$ (consistent with 0)

Theoretical Predictions

- Beam-normal prediction: Exchange of two photons occurs between lepton and the same quark
  - $A_n = \frac{\alpha_{\text{EM}} m_l |\vec{S}_T| \sin(\varphi_s)}{2Q} \frac{y^2\sqrt{1-y}}{1-y+\frac{1}{2}y^2} \frac{\sum_q e_q^3 q(x)}{\sum_q e_q^2 q(x)}$
  - A. Metz et al., Phys. Lett. B 643 (2006)
  - Prediction for A_n: 10^{-6}-10^{-7}
- Target-Normal Predictions (Neutron):
  1. Exchange of two photons occurs between lepton and the same quark
     - A. Afanasev et al., Phys. Rev. D77 (2008) : TNSSA ~ 10^{-4}
  2. Exchange of two photons occurs between lepton and different quarks
     - A. Metz et al. Phys. Rev. D86 (2012):TNSSA ~ 10^{-2}
- JLab 6 GeV target- normal SSA (Neutron) | Hermes target-normal SSA (Proton)
  - (-1.09 ± 0.38) × 10^{-2} (Non-zero: 2.89σ) | $(0.6 - 0.9) \pm (1.50-3.97) \times 10^{-3}$ (consistent with 0)
- Dominant process for target-normal SSA is still not well understood
  - **Assumption** is that the exchange of two photons occurs between the lepton and different quarks is **dominant** but not conclusive. **Need more experimental evidence**
- **Assumption** is that the exchange of two photons occurs between the lepton and a single quark for beam-normal SSA. **Need any experimental evidence to support**

Motivation

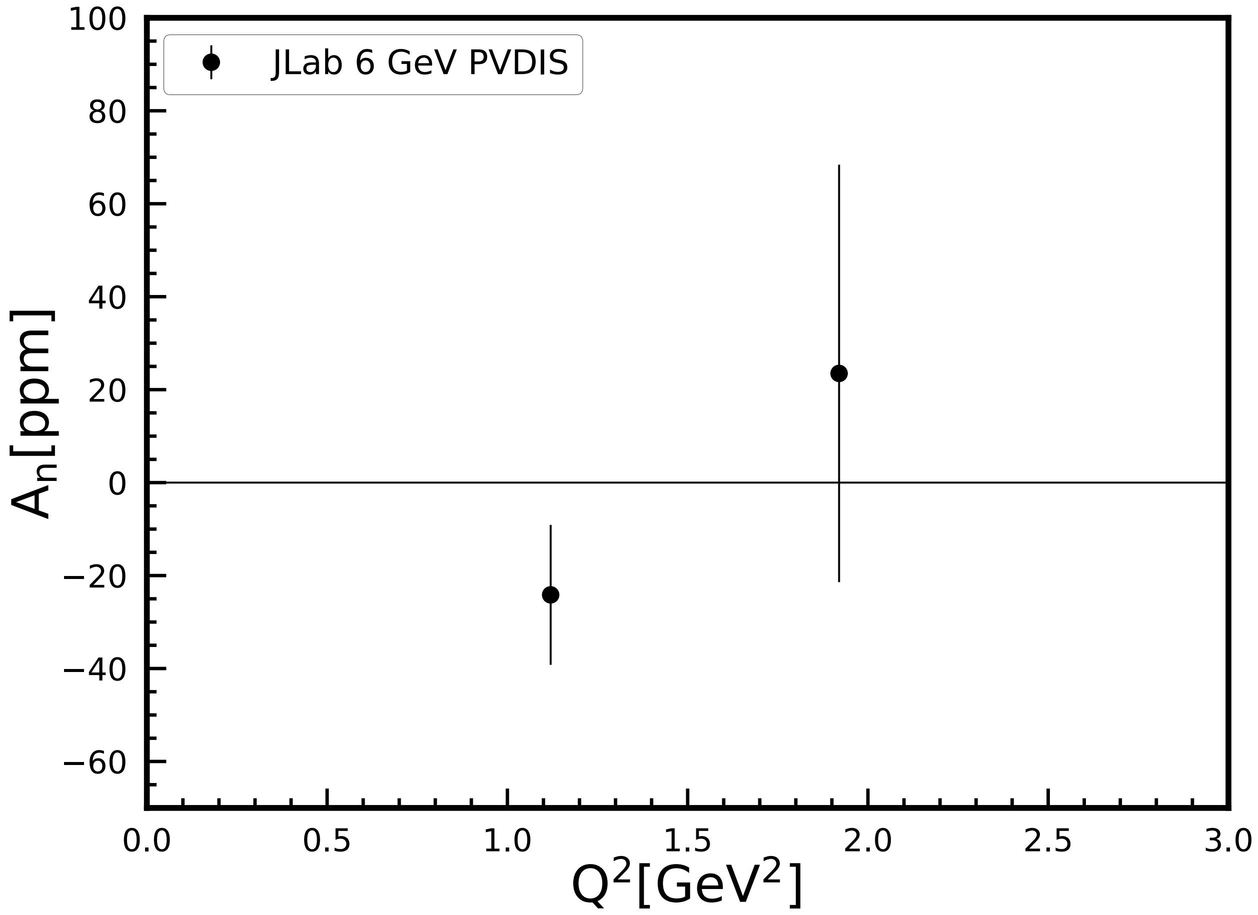
- (Almost) non-existent experimental evidence for the beam-normal SSA in DIS
- M. Schlegel, *Phys.Rev.D* 87 (2013) 3, 034006
  - "In principle, single-spin observables in inclusive DIS with either the **lepton** or nucleon being transversely polarized **are equally fundamental**"
- DIS TPE data are limited
  - "Measurement of A_n to **5 ppm would** provide very useful information. Even A_n to 10 ppm is a big step" Andrei Afanasev
- A high precision measurement of the beam-normal SSA would be impactful in
  - Understanding the dominant mechanism in BNSSA and TNSSA
  - Constraining TPE models
- A large SSA beyond leading twist could have implications to TMD measurements
  - SIDIS measurements of TMDs via SSA could require a separation of TPE and TMD effects

Normal Single Spin Asymmetries: DIS

- Investigations in the TPE date back to measurements in the 1960's
- Measurements:
  - Differences in the ratio of cross sections: $\frac{e^+}{e^-}$ or $\frac{\mu^+}{\mu^-}$
  - **Beam**- or target- normal single spin asymmetries
- Limited number of TPE measurements
  - BNSSA : (nearly) non-existent and **no planned measurements**
  - TNSSA : Measurements on proton and neutron (via ^{3}He)
    - Ay (E12-11-108A/E12-10-006 : Approved SoLID Run Group Experiment
    - Uncertainty: 10^{-4}-10^{-3} ($1.5 < Q^2 < 7.5$ GeV^2)

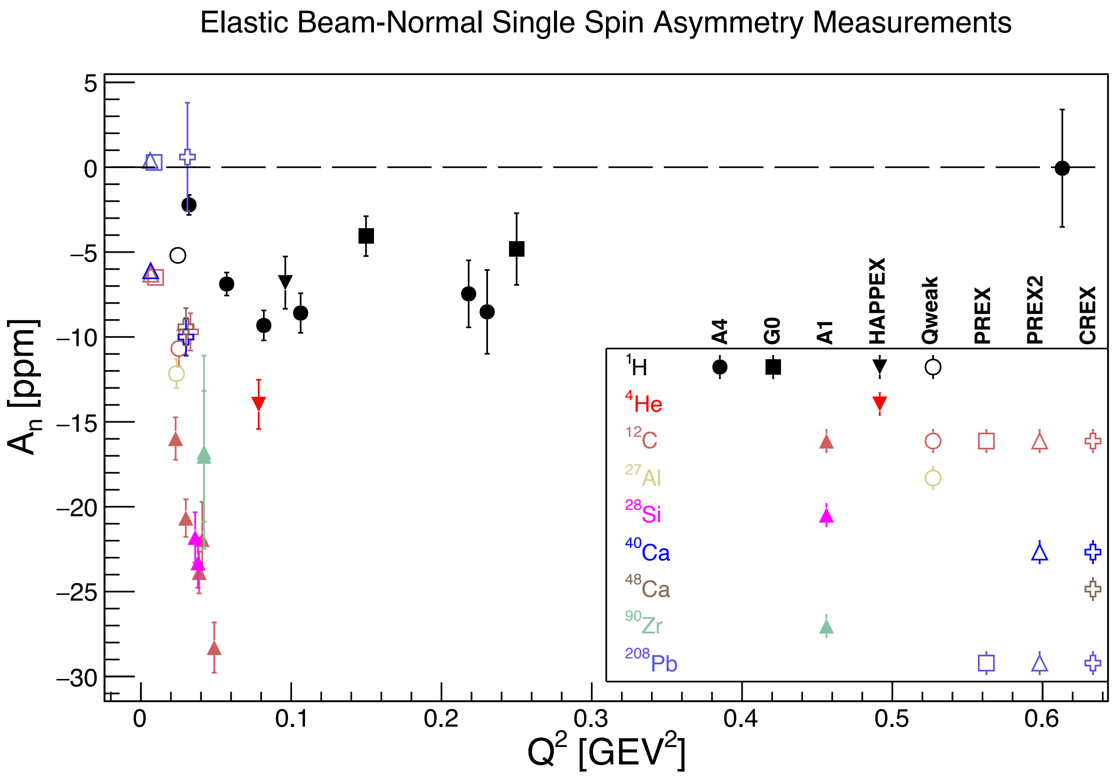
Beam-Normal Single Spin Asymmetry

Only DIS measurement
D. Wang et al., Phys. Rev. C 91 (2014)



Elastic Beam-Normal Single Spin Asymmetry

F. E. Maas et al., Phys. Rev. Lett. 94 (2005)
D. S. Armstrong et al., Phys. Rev. Lett. 99 (2007)
D. Androić et al., Phys. Rev. Lett. 107 (2011)
S. Abrahamyan et al., Phys. Rev. Lett. 109 (2012)
A. Esser et al., Phys. Rev. Lett. 121 (2018)
B. Gou et al., Phys. Rev. Lett. 124 (2020)
D. Androić et al., Phys. Rev. C 104 (2021)

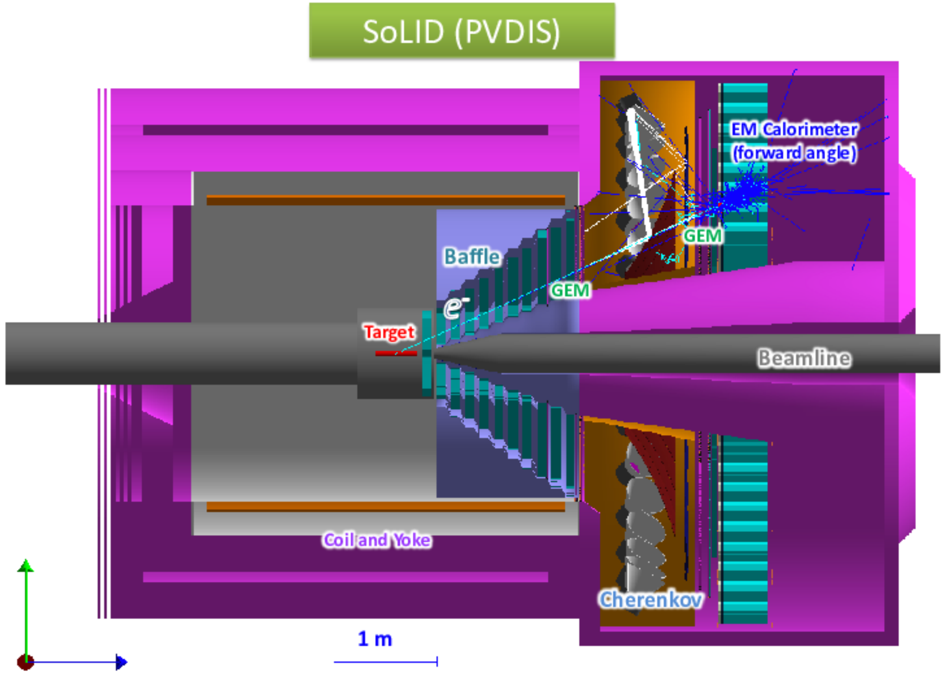


*Reproduce by: **Darren Upton**

Experimental Overview

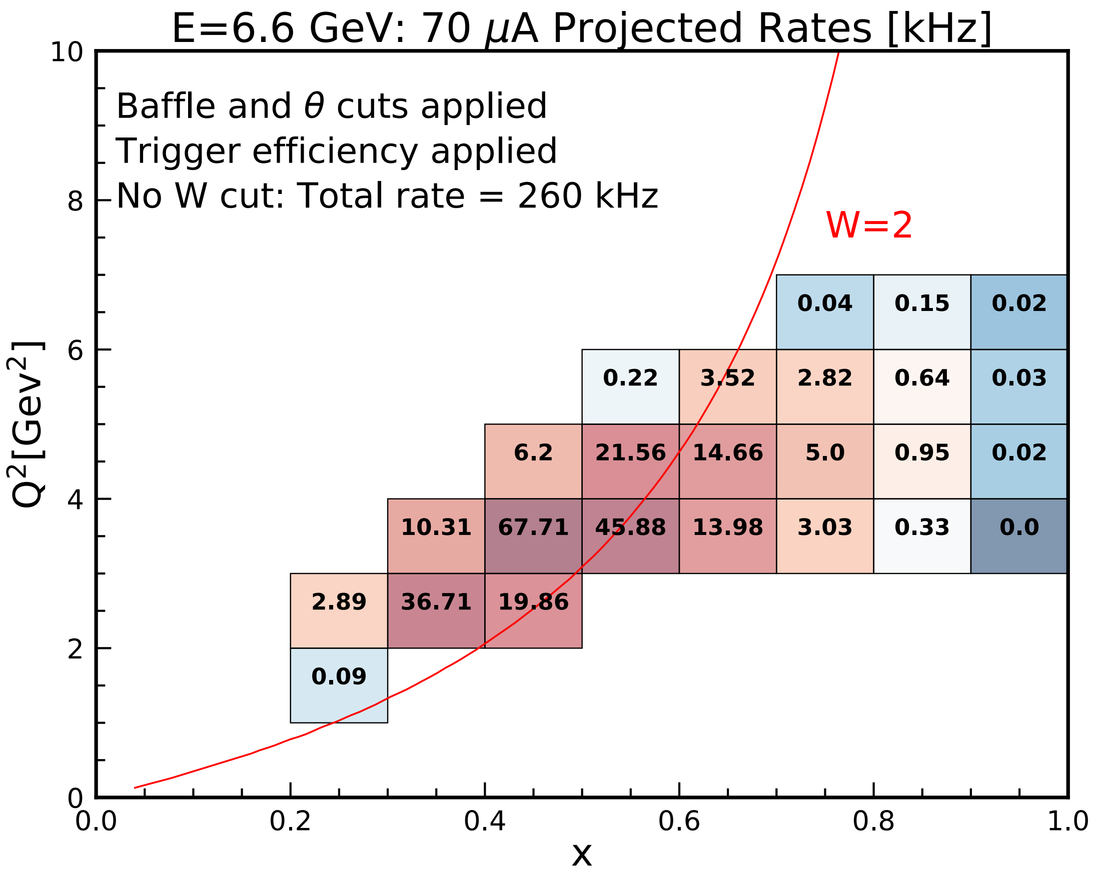
Experiment Overview: SoLID

- **First high precision beam-normal SSA measurement in DIS**
    - **Expected precision at the few ppm level**
- SoLID configuration: PVDIS
    - Scattering angle: 22°< θ < 35 °
    - Large azimuthal coverage
    - PVDIS 40-cm liquid hydrogen target
- Transversely polarized e$^-$ beam
- Beam Current
    - 70 μA
- Beam-normal SSA measured from the ϕ dependence
    - $\frac{\sigma^{\uparrow}-\sigma^{\downarrow}}{\sigma^{\uparrow}+\sigma^{\downarrow}} = A_n \sin(\varphi)$



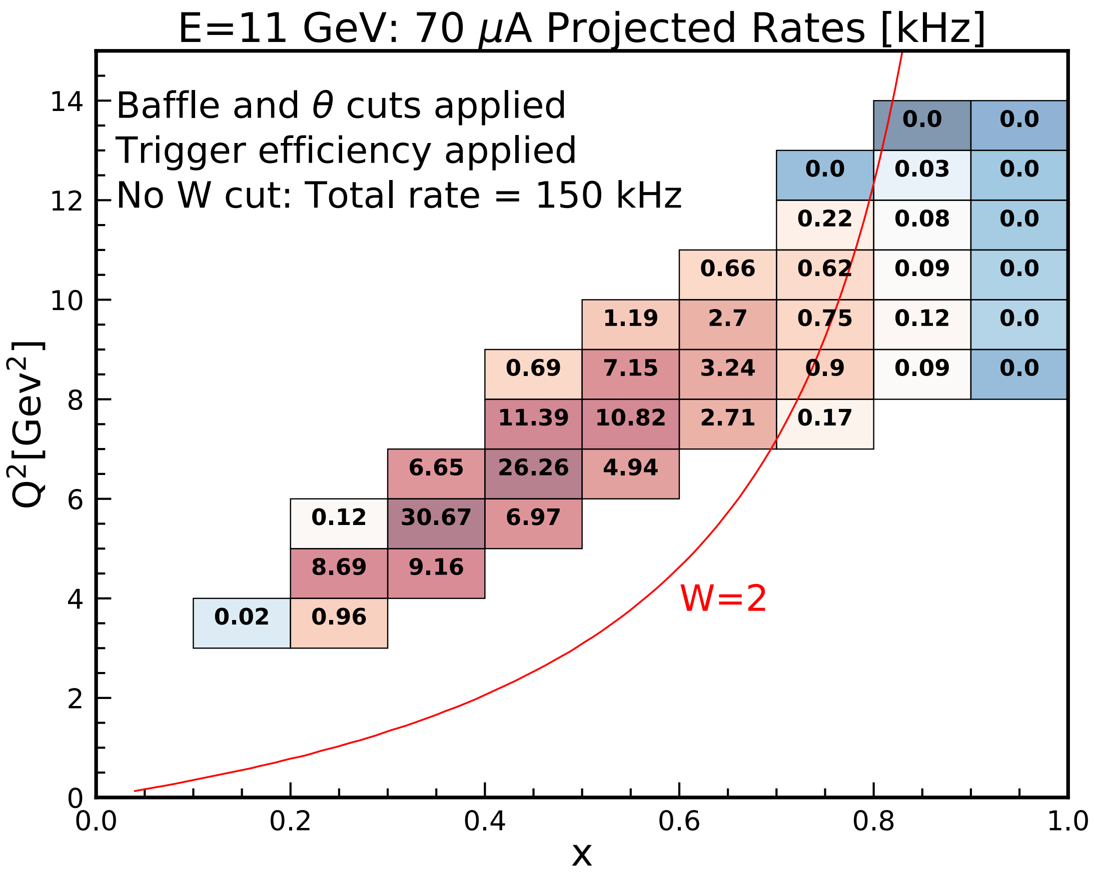
Experiment Overview: SoLID

- **First high precision beam-normal SSA measurement in DIS**
  - **Expected precision at the few ppm level**
- SoLID configuration: PVDIS
  - Scattering angle: 22°< θ < 35 °
  - Large azimuthal coverage
  - PVDIS 40-cm liquid hydrogen target
- Transversely polarized e^- beam
- Beam Current
  - 70 μA
- Beam-normal SSA measured from the ϕ dependence
  - $\frac{\sigma^{\uparrow}-\sigma^{\downarrow}}{\sigma^{\uparrow}+\sigma^{\downarrow}} = A_n \sin(\varphi)$



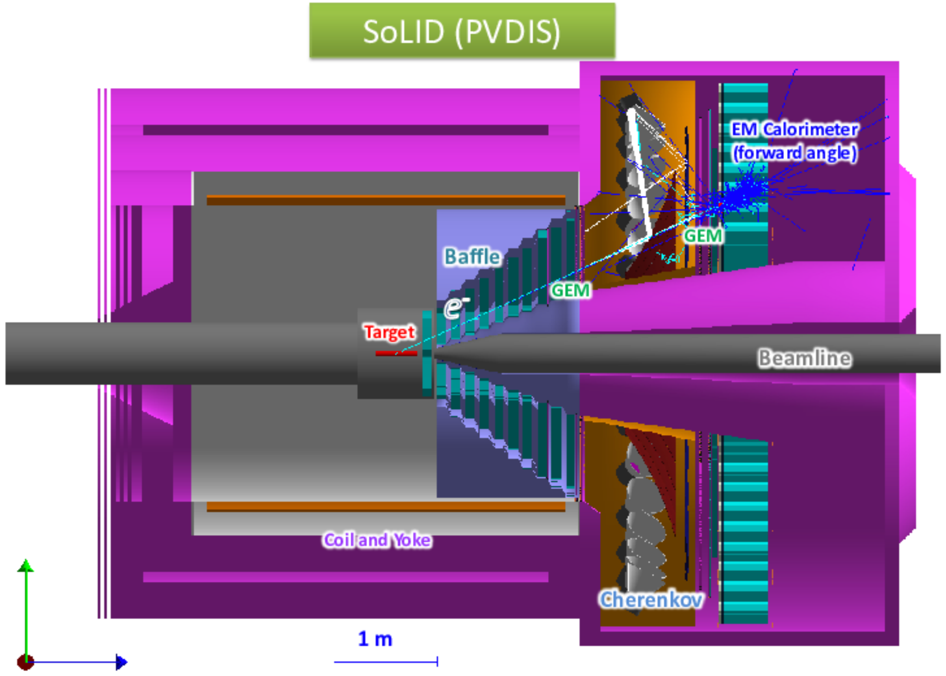
Experiment Overview: SoLID

- **First high precision beam-normal SSA measurement in DIS**
  - **Expected precision at the few ppm level**
- SoLID configuration: PVDIS
  - Scattering angle: 22°< θ < 35 °
  - Large azimuthal coverage
  - PVDIS 40-cm liquid hydrogen target
- Transversely polarized e^- beam
- Beam Current
  - 70 μA
- Beam-normal SSA measured from the ϕ dependence
  - $\frac{\sigma^{\uparrow}-\sigma^{\downarrow}}{\sigma^{\uparrow}+\sigma^{\downarrow}} = A_n \sin(\varphi)$



Experiment Overview: SoLID

- High luminosity and large azimuthal coverage of SoLID key to beam-normal SSA measurement
  - $\mathcal{L} \sim 5.4 \cdot 10^{38}$ cm^{-2} s^{-1}
- SoLID provides a unique opportunity to perform a precision measurement of the beam-normal SSA in deep inelastic scattering
- *TAC: "Overall the proposal has no major technical show-stopper"*



Systematic Uncertainties

Systematic	Uncertainty
Target endcaps	5%
Polarimetry	3%
Radiative Corrections	1-2%
Particle background	1%
Q^2 determination	0.2%
Target polarization	Under 0.1 ppm
Total Systematic	**(6.0 – 6.2)%**

Uncertainties dominated by statistics

Systematic Uncertainties

Systematic	Uncertainty
Target endcaps	5%
Polarimetry	3%
Radiative Corrections	1-2%
Particle background	1%
Q^2 determination	0.2%
Target polarization	Under 0.1 ppm
Total Systematic	**(6.0 – 6.2)%**

	E_{Beam} = 6.6 GeV	
Day	Activity	Time (Hours)
1	Spin Dance	16
1	90° Wien Rotation	4
8	90° Wien Rotation	4
8	Moller Measurement	12
8	90° Wien Rotation	4
15	90° Wien Rotation	4
15	Moller Measurement	12
15	90° Wien Rotation	4
22	Spin Rotator Flip	4
22	Spin Dance	16
22	90° Wien Rotation	4
29	90° Wien Rotation	4
29	Moller Measurement	12
29	90° Wien Rotation	4
Total (6.6 GeV)		104 hours (4.3 days)
	E_{Beam} = 11.0 GeV	
Day	Activity	Time (Hours)
1	Spin Dance	16
1	90° Wien Rotation	4
8	90° Wien Rotation	4
8	Moller Measurement	12
8	90° Wien Rotation	4
15	90° Wien Rotation	4
15	Moller Measurement	12
15	90° Wien Rotation	4
22	Spin Rotator Flip	4
22	Spin Dance	16
22	90° Wien Rotation	4
Total (11.0 GeV)		84 hours (3.5 days)
Grand Total (6.6 GeV + 11.0 GeV)		3.9 PAC days

Stability of transverse polarization is equivalent to longitudinal polarization

Systematic Uncertainties

Systematic	Uncertainty
Target endcaps	5%
Polarimetry	3%
Radiative Corrections	1-2%
Particle background	1%
Q^2 determination	0.2%
Target polarization	Under 0.1 ppm
Total Systematic	**(6.0 – 6.2)%**

Added In response to TAC and reader review

<u>Radiative Correction Factor</u>

6.6 GeV

RC varies between 1.7 and 2.5%

11 GeV

RC varies between 1.6% and 10.0%

Systematic Uncertainties

Systematic	Uncertainty
Target endcaps	5%
Polarimetry	3%
Radiative Corrections	1-2%
Particle background	1%
Q^2 determination	0.2%
Target polarization	Under 0.1 ppm
Total Systematic	**(6.0 – 6.2)%**

Uncertainties dominated by statistics

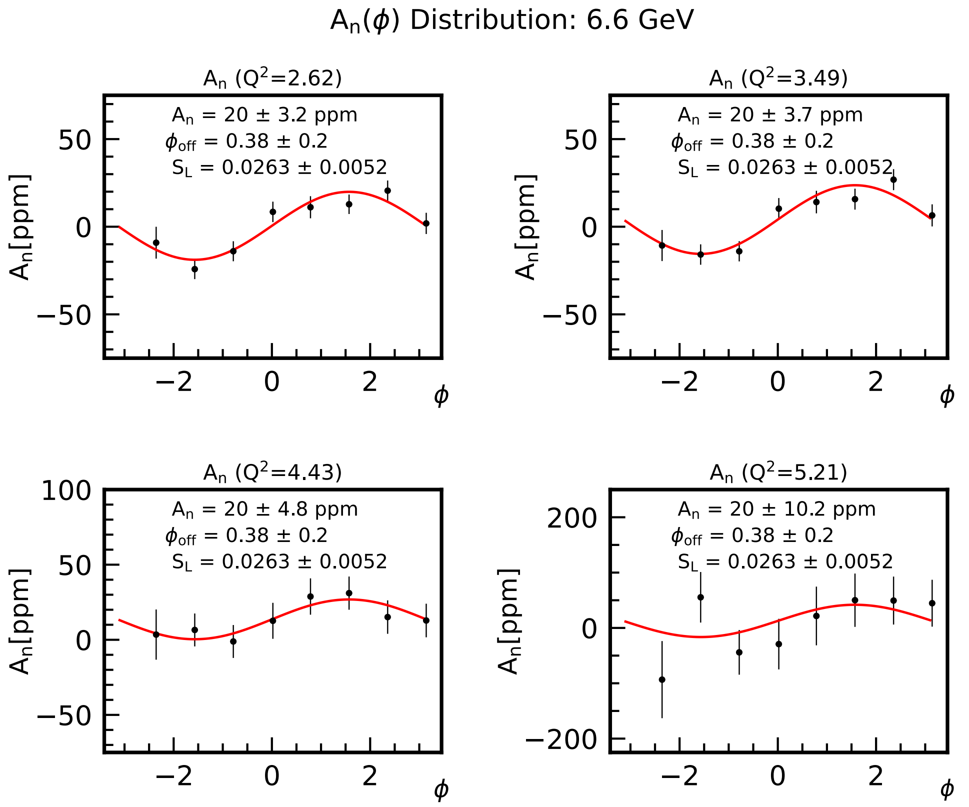
Projected Results

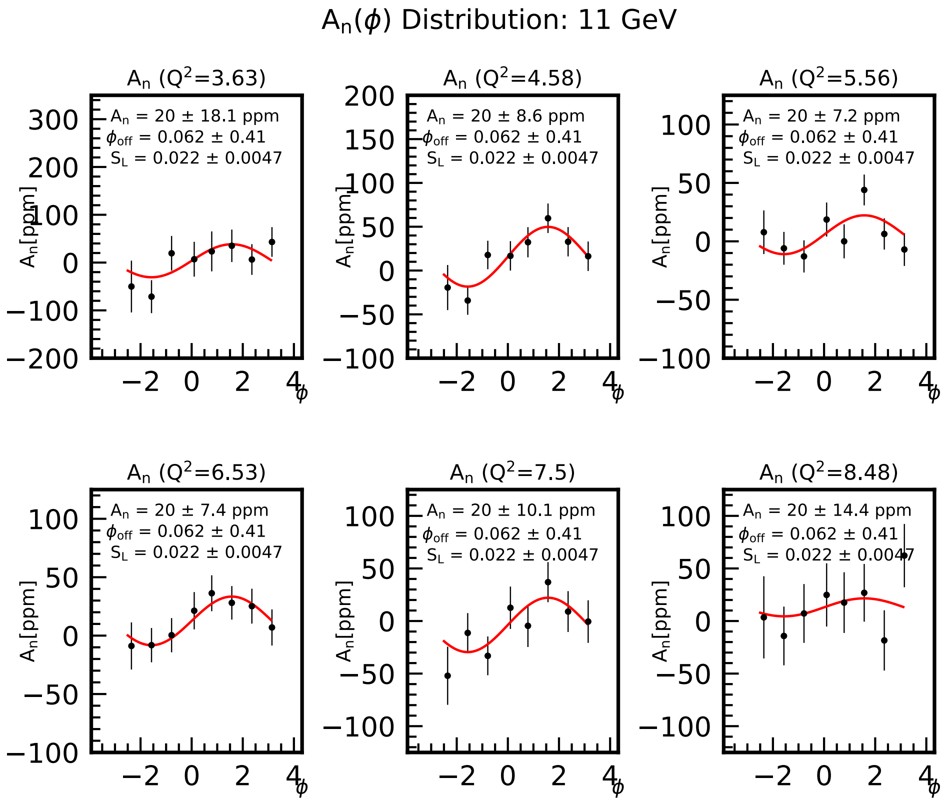
SoLID simulation based on PVDIS configuration

40-cm LH_2 target

W >2, 22°< θ < 35 °, P_b=85%

Beam-normal SSA extracted from multi-parameter fit: $C_n \sin(\varphi + \varphi_{\text{offset}}) + S_L A_{\text{PVDIS}}$





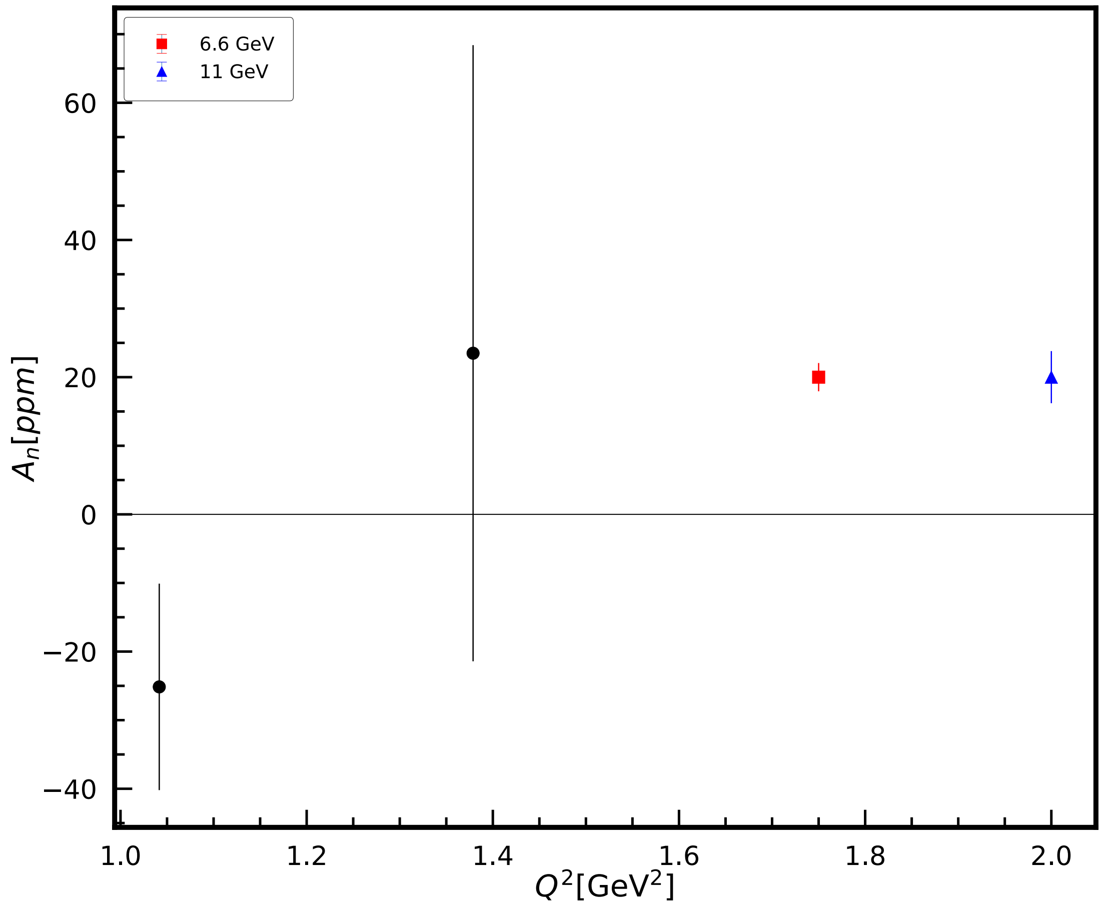
Projections: Result and Uncertainty

<u>Combining Q^2 bins in each energy setting</u>

$A_n = A_{measured} \pm 2.06$ ppm : 6.6 GeV

$A_n = A_{measured} \pm 3.80$ ppm : 11 GeV

Opportunity to measure non-zero BNSSA



Projected results not at expected Q^2 values

Projections: Result and Uncertainty

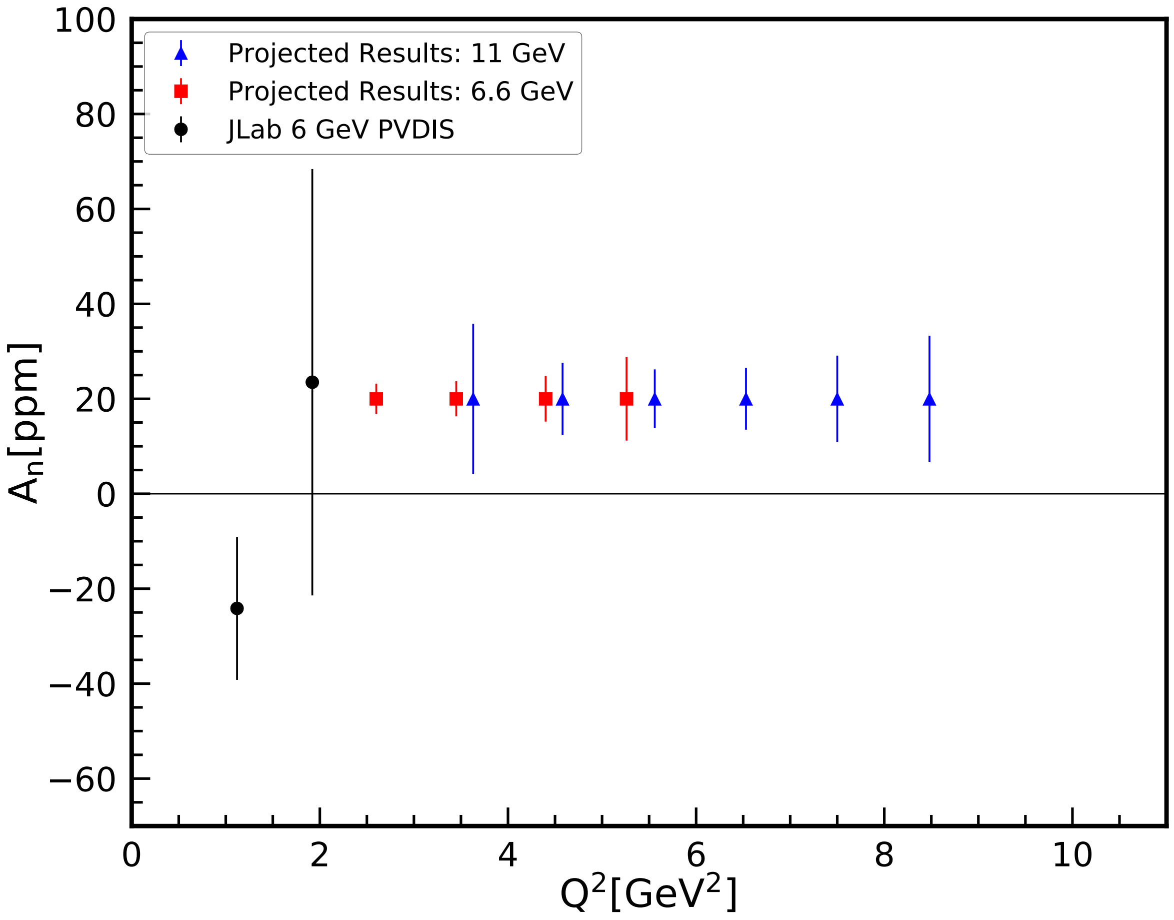
Combining Q^2 bins in each energy setting

$A_n = A_{measured} \pm 2.06$ ppm : 6.6 GeV
$A_n = A_{measured} \pm 3.80$ ppm : 11 GeV

Opportunity to measure non-zero BNSSA

TAC Theory: "…it will be interesting to observe the Q^2 dependence of the asymmetry empirically, to test whether the scattering takes place on a single quark or involved more complicated nonperturbative multi-parton interactions."

The opportunity to observe a Q^2 dependence with sufficient precision is primarily due to the design SoLID



Beam Time Request

Purpose	Time (Days)	Energy (GeV)	Beam Current (μA)
Commissioning	2	varies	As needed
Polarimetry	4	varies	As needed
Pass Change	0.67	N/A	N/A
Reverse SoLID Polarity	0.67	N/A	N/A
Reverse polarity run	0.33	6.6	70
Reverse polarity run	0.33	11	70
40-cm LH_2 Production	17	6.6	70
40-cm LH_2 Production	11	11	70

A total of 38 PAC days

Summary

- The proposed experiment would be the **first high-precision measurement** of the beam-normal single spin asymmetry in deep inelastic scattering
- No other planned measurements
- The beam-normal single spin asymmetry provides an essential tool for studying the two-photon exchange effect
  - Will add a new observable to the TPE landscape
- Important for theoretical models
  - Further insight into dominant mechanism (single or two quark)
  - Complementary to the already approved target-normal single spin asymmetry
- Theoretical support
  - INT: PVDIS at JLab 12 GeV and beyond
  - Radiative Corrections from medium to high energy experiments
  - Drive interest of both experimental and theoretical communities
- **Jefferson Lab and SoLID make this a realistic measurement**

Thank You

Projections

- Estimated the projected impact
- Utilized SoLID simulation for PVDIS configuration
  - 40-cm LH_2 Production
  - W >2, 22°< θ < 35 °, P_b=85%
- Generate pseudo-data:
  - $A^{i^{th}\text{bin}}_{raw,pseudo-data} = 20_{\text{ppm}} \sin(\phi) + r_i \Delta^i_{\text{stat}} + r_b\, A^i_{p,\text{PVDIS}}$
- Perform multi-parameter fit:

- r_i and r_b: random number drawn from Normal distribution
- r_b common across all bins at same beam energy

$$
\begin{aligned}
f_1 &= C_1 \sin(\varphi + \varphi_{\text{offset}}) + S_L A_{\text{PVDIS}} \\
f_2 &= C_2 \sin(\varphi + \varphi_{\text{offset}}) + S_L A_{\text{PVDIS}} \\
&\;\vdots \\
f_N &= C_N \sin(\varphi + \varphi_{\text{offset}}) + S_L A_{\text{PVDIS}}
\end{aligned}
$$

Systematic Uncertainties

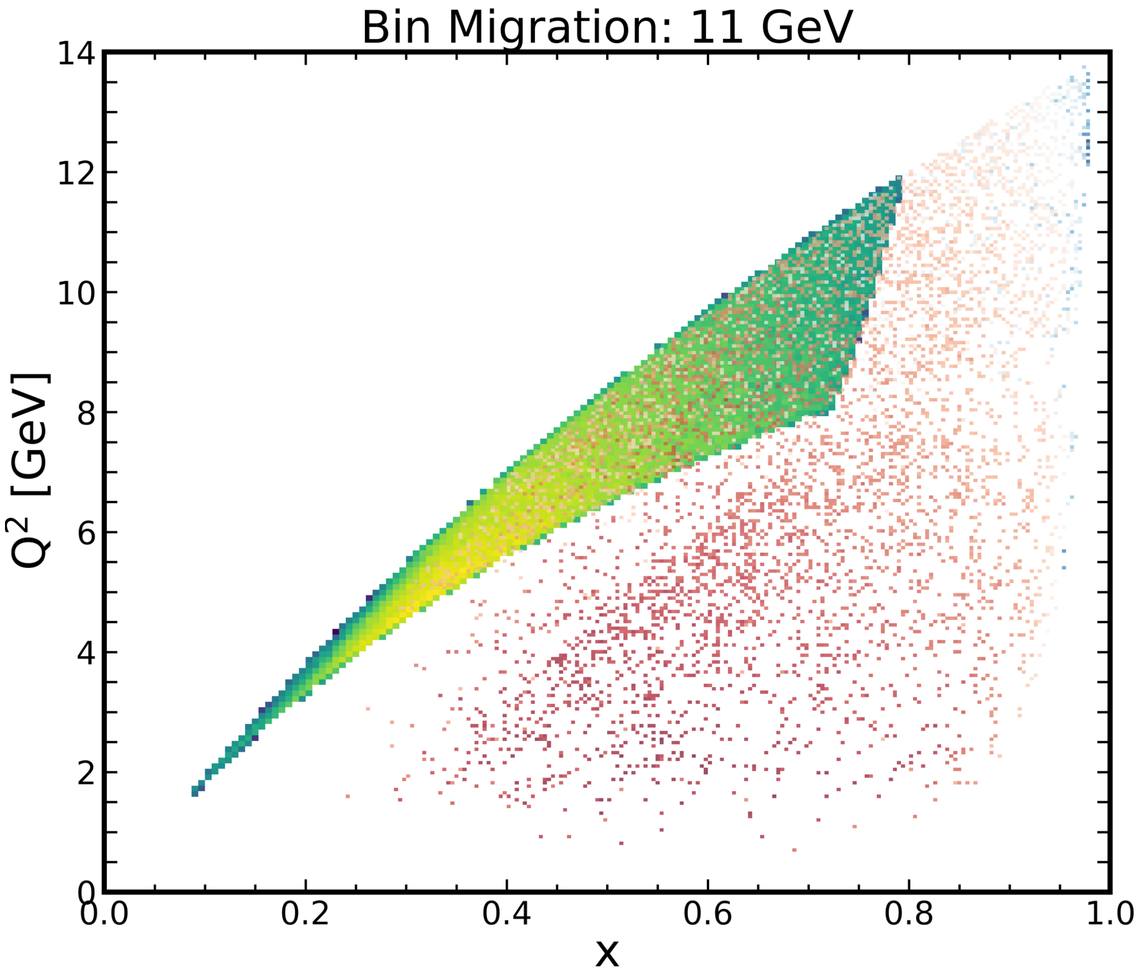
Systematic	Uncertainty
Target endcaps	5%
Polarimetry	3%
Radiative Corrections	1-2%
Particle background	1%
Q^2 determination	0.2%
Target polarization	Under 0.1 ppm
Total Systematic	**(6.0 – 6.2)%**

Target Endcaps: Aluminum

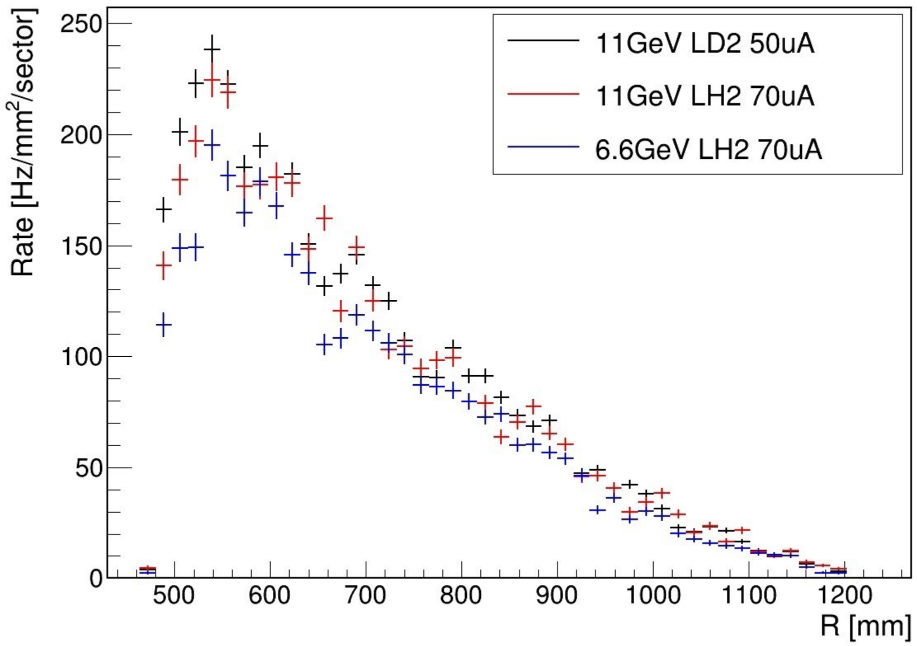
Upstream: 120μm

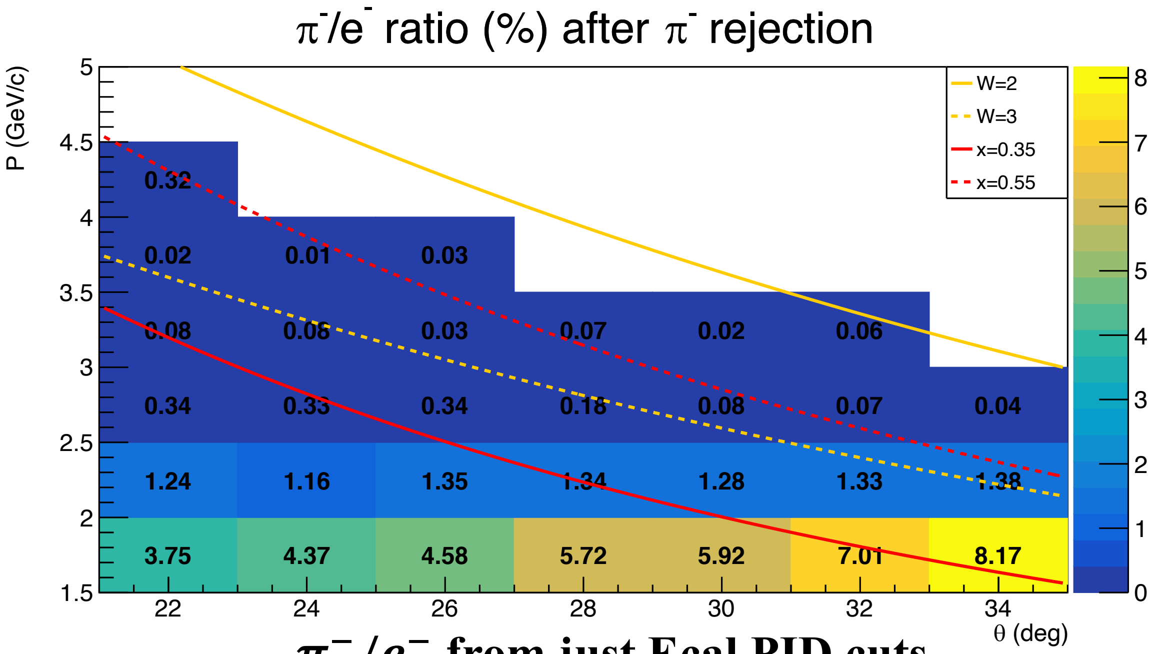
Downstream: 150μm

Radiative Corrections



Background

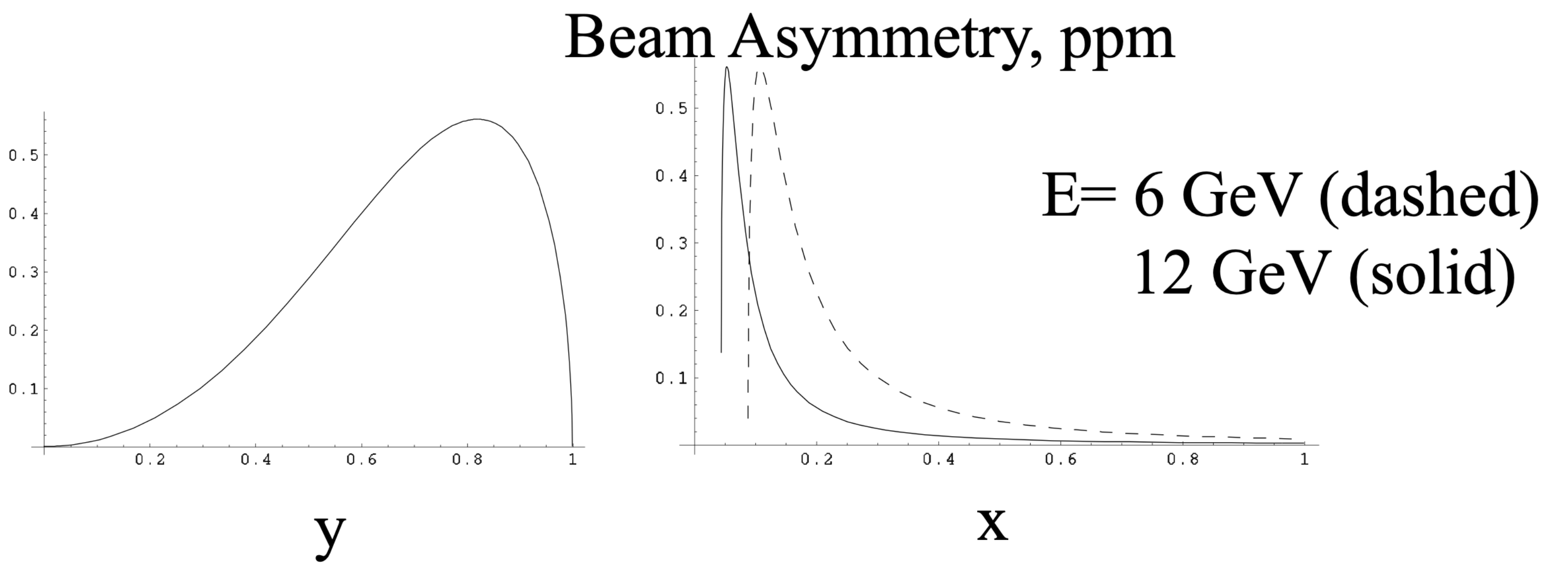




π^-/e^- **from just Ecal PID cuts**

Total background expected to be smaller than PVDIS LD2

Logarithmic Enhancement

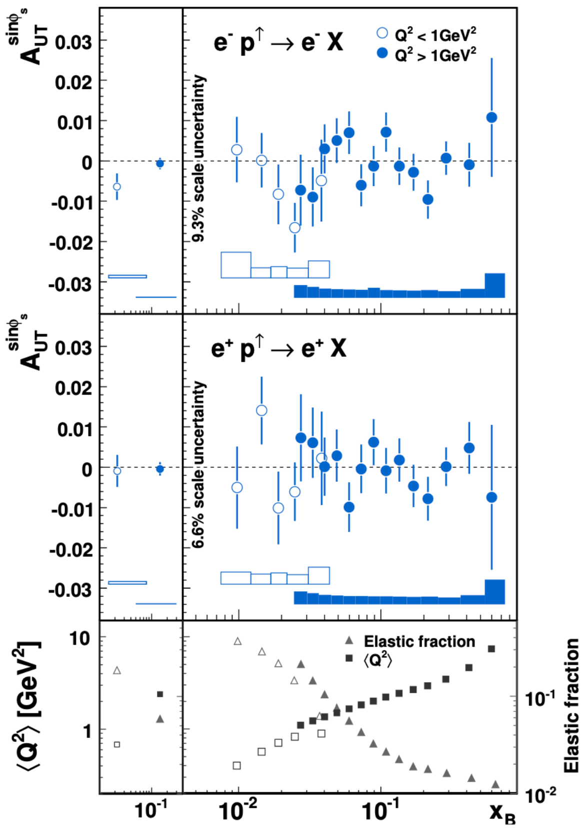


- The leading-twist calculation predicts the effect around 1⁄2 ppm
- Regge-limit (optical theorem): 10-100ppm: AA PRB 599 (2004) 48
- PVDIS at JLAB *Phys. Rev.* C 91 (2015) ~20ppm, large uncertainty
- Large-log enhancements leads to the estimates

  A_n~0.5ppm (leading twist) 0.5ppm log(Q2/me2)~8ppm

*Slide from Andrei Afanasev: **Inclusive Single-Spin Asymmetries and Nucleon Structure in Electron Scattering** – **INT Workshop**

Target-Normal Single Spin Asymmetry



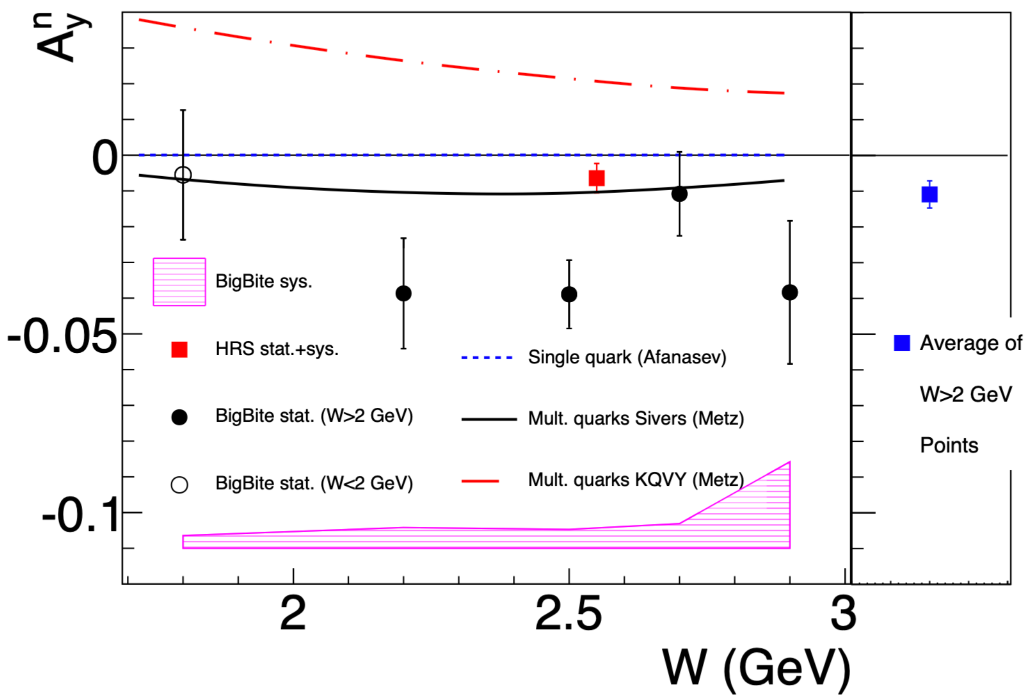
A_y^p = (0.6 – 0.9) ± (1.50-3.97)× 10^{-3}

A. Airapetian et al., Phys. Lett. B682, 351 (2010)

Neutron Asymmetries extracted:

$$A_y^{^3\text{He}} = (1 - f_p) P_n A_y^n + f_p P_p A_y^p$$

$P_p(P_n)$ = Effective proton (neutron) polarization



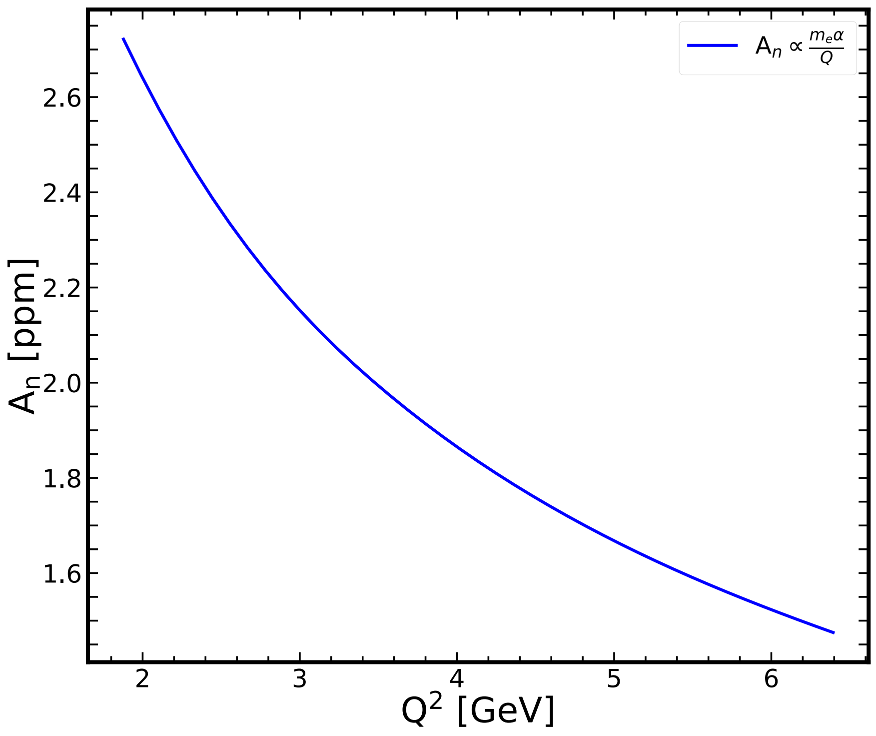
A_y=(-1.09 ± 0.38) × 10^{-2}

Non-zero: 2.89σ

Katich et al., Phys. Rev. Lett. 113 (2014)

Enhancement of A_n

- A. Metz et al., Phys. Lett. B 643 (2006)
- Exchange of two photons occurs between lepton and the same quark
- $A_n \sim (10^{-6}\text{-}10^{-7})$
- M. Schlegel and A.Metz (2009)
  - "One might also speculate about enhanced results from effects beyond the naive parton model. In Refs. [8, 9, 10, 11] (double) logarithms of the type $\log(Q^2/m^2)$ were advocated in connection with the transverse beam SSA in elastic lepton-nucleon scattering. Such logarithmic terms might also increase the beam SSA in DIS considered here. However, further work is required in order to decide whether and how precisely such effects show up for the DIS case"
- TNSSA
  - "No very realistic numerical estimate of all the contributions. Therefore, it is difficult to say which of the two contributions (coupling to different quarks vs coupling to the same quark) dominates."



Target-Normal Single Spin Asymmetry

Highest Q^2 point is consistent with the GPD calculations
[Y.W. Zhang et al., Phys. Rev. Lett. 115 (2015)]